The Solar Neutrino Day/Night Effect in Super-Kamiokande

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The time variation of the elastic scattering rate of solar neutrinos with electrons in Super-Kamiokande-I was fit to the day/night variations expected from active two-neutrino oscillations in the Large Mixing Angle region. Combining Super-Kamiokande measurements with other solar and reactor neutrino data, the mixing angle is determined as $\sin^2\theta = 0.276^{+0.033}_{-0.026}$ and the mass squared difference between the two neutrino mass eigenstates as $\Delta m^2 = 7.1^{+0.6}_{-0.5}\times 10^{-5}\text{eV}^2$. For the best fit parameters, a day/night asymmetry of $-1.7\pm 1.6(\text{stat})^{+1.3}_{-1.2}(\text{syst})\%$ was determined from the Super-Kamiokande data, which has improved statistical precision over previous measurements and is in excellent agreement with the expected value of -1.6%.

1. Introduction

The combined analysis of all solar neutrino experiments [1] gives firm evidence for neutrino oscillations. All data are well described using just two neutrino mass eigenstates and imply a mass squared difference between $\Delta m^2 = 3\times 10^{-5}\text{eV}^2$ and $\Delta m^2 = 1.9\times 10^{-4}\text{eV}^2$ and a mixing angle between $\tan^2\theta = 0.25$ and $\tan^2\theta = 0.65$ [2]. This region of parameter space is referred to as the Large Mixing Angle solution (LMA). The rate and spectrum of reactor anti-neutrino interactions in the KamLAND experiment [3] are also well reproduced for these mixing angles and some of these Δm^2. Over the Δm^2 range of the LMA, solar ^{8}B neutrinos are ≈100% resonantly converted into the second mass eigenstate by the large matter density inside the sun [4]. Therefore, the survival probability into ν_e is $\approx \sin^2\theta$. However, due to the presence of the earth's matter density, the oscillation probability at an experimental site on earth into ν_e differs from $\sin^2\theta$ during the night. Since Super-Kamiokande experiment is primarily sensitive to ν_e's, this induces an apparent dependence of the measured neutrino interaction rate on the solar zenith angle (often a regeneration of ν_e's during the night). Recently, Super-Kamiokande employed a maximum likelihood fit to the expected solar zenith angle dependence on the neutrino interaction rate [5]. Herein, the statistical uncertainty was reduced by 25% compared to previous measurement of the day/night asymmetry [2] which consists of two flux measurements in two separate data samples (day and night). It would require almost three more years of running time to obtain a similar uncertainty reduction. Also the GNO, SAGE, and SNO collaborations [1] reported updated neutrino interaction rates.

Super-Kamiokande (SK) is a 50,000 ton water Cherenkov detector described in detail elsewhere [6]. SK measures the energy, direction, and time of the recoil electron from elastic scattering of solar neutrinos with electrons by detection of the emitted Cherenkov light. Super-Kamiokande started taking data in April, 1996. In this report, the full SK-I low energy data set consisting of 1496 live days (May 31$^{\text{st}}$, 1996 through July 15$^{\text{th}}$, 2001) is used.

2. Day/Night Asymmetry

The solar zenith angle θ_z between the solar direction and the vertical direction defines the path length of the solar neutrino inside the earth. During the day ($\cos\theta_z < 0$) this path length is zero, during the night ($\cos\theta_z > 0$) it varies between zero and (up to) the diameter of the earth. The day/night rate asymmetry is defined as

$$A_{\text{DN}} = \frac{D-N}{0.5(D+N)}$$

where D (N) refers to the average neutrino interaction rate during the day (night). If the neu-

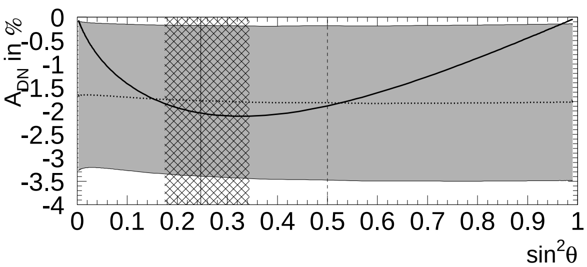

Figure 1. Fitted SK Day/Night Asymmetry as a Function of Mixing. The Δm^2 is $6.3 \times 10^{-5}\mathrm{eV}^2$. The gray band is the $\pm 1\sigma$ SK measurement. The hatched area corresponds to the $\pm 1\sigma$ uncertainty of the ^{8}B flux by Junghans et al [7]. The solid black line shows the oscillation prediction of the day/night asymmetry.

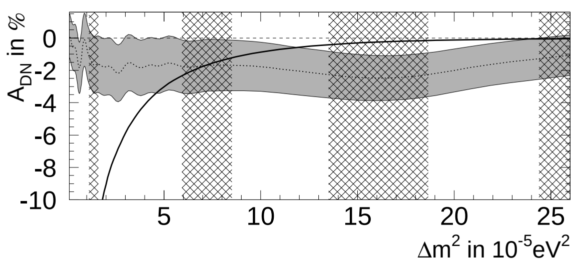

Figure 2. Fitted SK Day/Night Asymmetry as a Function of Δm^2. The gray band is the $\pm 1\sigma$ SK measurement. The hatched area corresponds to the 95% allowed contours reported by the KamLAND collaboration. The solid black line shows the oscillation prediction of the day/night asymmetry.

trino interaction rate during the night varies significantly from the average night rate N, and if the functional form (shape) of this variation is known, the amplitude of this time variation of the rate can be determined more accurately then just calculating A_{DN} from the average rates. These conditions are met for two-neutrino oscillations in the LMA region. In [5] a maximum likelihood fit to the SK data finds a day/night amplitude equivalent to $A_{\mathrm{DN}} = -1.8 \pm 1.6(\mathrm{stat})^{+1.3}_{-1.2}(\mathrm{syst})\%$. The fit assumes $\Delta m^2 = 6.3 \times 10^{-5}\mathrm{eV}^2$ and $\tan^2\theta = 0.55$. The asymmetry calculated from the measured average day and night rates on the other hand is $A_{\mathrm{DN}} = -2.1 \pm 2.0(\mathrm{stat})^{+1.3}_{-1.2}(\mathrm{syst})\%$ [2]. It assumes a step function for the time variation and therefore does not reflect any oscillation parameters. The dependence of the fitted day/night amplitude on the mixing angle $\sin^2\theta$ is shown in Figure 1. Overlaid are the predicted asymmetries and the solar model constraint of the ^{8}B neutrino flux from Junghans et al [7]. The Δm^2 dependence is stronger as can be seen in Figure 2. Overlaid are the predicted asymmetries and bands (typically called LMA-0, LMA-I, LMA-II, etc) corresponding to the KamLAND 95% allowed contours: the SK day/night measurement excludes LMA-0, and favors LMA-I.

3. Full Oscillation Analysis

An oscillation analysis of the SK data by itself is found in [5]. It describes the solar zenith angle variation with a likelihood, while the spectrum is fit with a χ^2 method. Since the combined solar neutrino oscillation analysis of [5] was performed, the neutrino interaction rate measurements of several experiments improved in precision. In particular, the SNO collaboration reported a more precise neutral-current interaction rate on deuterium employing salt to enhance neutron detection. Figure 3 shows in (dark gray) the allowed regions at 95% C.L. resulting from the combination of experimental data from Gallex/GNO, SAGE, the Homestake experiment and SK. It relies on the ^{8}B flux from Junghans and six low energy neutrino fluxes of the standard solar model [7]. Also shown is a combined fit to SK data, the new salt-enhanced SNO rate measurements, and the SNO day/night asymmetry. This fit does not rely on any neutrino flux prediction. Both analyses yield a unique allowed region – the LMA solution – and agree very closely in mixing. The SK/SNO analysis provides somewhat stronger constraints on Δm^2. Assuming CPT invariance, both fits are then combined with a binned likelihood analysis [8] of the KamLAND

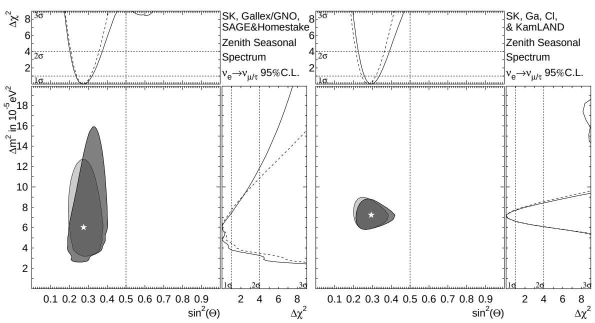

Figure 3. Allowed Regions at 95% C.L. from solar neutrino data (left) and solar neutrino & KamLAND (right) reactor neutrino data. The functions at the top and right of each panel are the mariginalized $\Delta\chi^2$ distributions. The dark gray areas/solid lines use the solar neutrino data from Gallex/GNO, SAGE, Homestake & SK the SSM neutrino fluxes (and the Junghans ^{8}B flux constraint), the light gray areas/dashed lines) solar measurements from SK & SNO and no neutrino flux constraints from solar models.

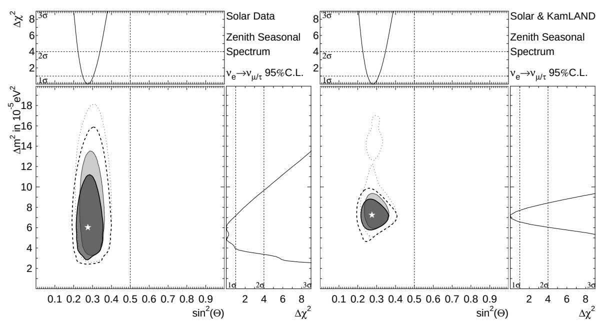

Figure 4. Allowed Regions at 95% (dark gray, solid) and 99.73% C.L. (dashed) from solar data (left) and solar & KamLAND measurements (right). The solar data includes the SNO salt-phase measurements. Overlaid are the corresponding regions reported by the SNO collaboration (light gray and dotted contours) with a weaker Δm^2 limit. The functions at the top and to the right of each panel are the mariginalized $\Delta\chi^2$ functions.

reactor anti-neutrino measurements [3], the results of which are shown in the right panel. In either case, only LMA-I remains allowed.

SNO has also published a combined oscillation analysis, which uses the SK zenith spectrum χ^2 instead of the likelihood employed in this report. Figure 4 compares allowed areas of the combined fit to all data using the SK likelihood (dark gray areas) with SNO's contours at 95% C.L. and 3σ: the Δm^2 constraints get stronger when the SK zenith spectrum is replaced by the SK likelihood. When combined with KamLAND, the LMA-I is favored over all other solutions by 3.5σ. The 3σ-allowed LMA-II contour from SNO's analysis disappears, when the SK likelihood is used. The oscillation χ^2 is Gaussian; the parameters are determined as $\Delta m^2 = 7.1^{+0.6}_{-0.5} \times 10^{-5}\mathrm{eV}^2$ and $\sin^2\theta = 0.276^{+0.033}_{-0.026}$. At those parameters, the day/night asymmetry is expected to be -1.6% while the amplitude fit to SK data yields $-1.7 \pm 1.6(\mathrm{stat})^{+1.3}_{-1.2}(\mathrm{syst})\%$.

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